DETECTING EFFICIENCY

OF THE RESISTANCE-CAPACITY COUPLED AMPLIFIER

TO 6000 METERS.

DISSERTATION

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1. Introductory.

The detecting efficiency of the resistance-capacity coupled electron tube amplifier has been discussed by E. O. Hulburt.* He derived a formula which indicated the connection between it and the constants of the electron tubes and the coupling circuits. His experiments showed that the theoretical relation held in the region from 400 to 1600 meters.

The detecting efficiency was defined by the relation $\lim_{A \to 0} \frac{b_0}{A^2}$ in which A and b_0 are the amplitudes, respectively, of the input grid potential and of the rectified component of the output plate current.

Consider the high frequency amplifier of two tubes as shown in Figure 1. For this type of amplifier Hulburt derived the following formula, subject to the conditions that there be no rectification in the first tube and no grid filament current in the second tube

$$\frac{b_0}{A^2} = n\,k^2 g_1^2 \left[\frac{(g_2g_3 - x_4x_5)^2 + \left[x_4(g_2 + g_3) + x_5g_2\right]^2}{\dfrac{(g_2g_3 - x_4x_5 + g_1g_3)^2 + \left[x_4(g_1 + g_2 + g_3) + x_5(g_1 + g_2)\right]^2}{\left(g_2 + g_3 + \frac{x_5}{x_4}g_2\right)^2 + \left(x_5 - \frac{g_2g_3}{x_4}\right)^2}} \right]$$

in which A is the amplitude of the radio frequency potential impressed on the grid of the first tube, b_0 is the rectified component of the resulting radio frequency current in the plate

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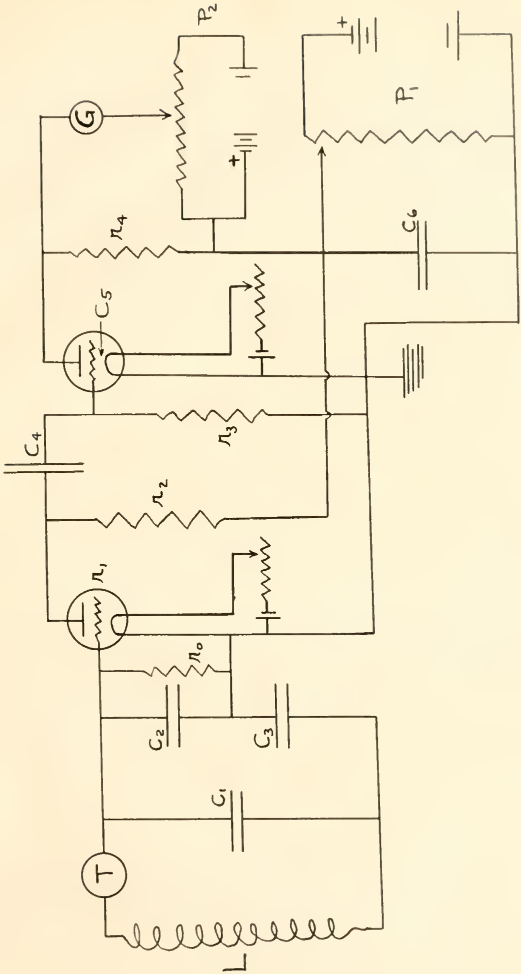
* Phys. Rev. 18, 165, 1921.

FIGURE 1



circuit of the second tube; k is the amplification constant of the first tube. r_1 is the internal resistance of the first tube from filament to plate. C_5 is the filament-grid capacity of the second tube. Resistances r_2 and r_3 and capacity C_4 are as shown in Figure 1.

Let $\frac{\omega}{2\Pi}$ be the frequency of the impressed voltage.

Let

$$\frac{1}{r_1} = g_1 \qquad \omega C_4 = X_4$$

$$\frac{1}{r_2} = g_2 \qquad \omega C_5 = X_5$$

$$\frac{1}{r_3} = g_3$$

One term has not been defined, which is

$$n \doteq \frac{b_o}{E g^2}$$

where E_g is the amplitude of potential impressed on the grid of the second tube. n does not depend on the frequency of the impressed voltage. (See Figure 6)

Let

$$g_2\, g_3 - x_4\, x_5 \doteq a$$

$$x_4\, (\, g_2 + g_3\,) + x_5\, g_2 \equiv b$$

Then, more accurately, the formula may be written

$$\frac{b_o}{A^2} = n\, K^2 g^2 \quad \frac{\dfrac{a\,(\,a + g_1 g_3) + b\,(\,b + x_4 g_1 + x_5 g_1\,)}{(\,a + g_1 g_3)^2 \quad (\,b + x_4 g_1 + x_5 g_1\,)^2}}{(\,g_2 + g_3 + \frac{x_5}{x_4}\, g_2)^2 + (\,x_5 - \frac{g_2 g_3}{x_4})^2} \tag{2}$$

It is to be noticed that this formula gives the detecting efficiency in terms of the constants of the electron tubes and the coupling circuits. Also Formula (1) is an approximation of (2), the use of which is justified under obvious conditions.

The object of this paper is to make the experimental measurements necessary in order to test Formula (1) for long wave-lengths, and to this end measurements were made from 1000 to 6200 meters.

2. Apparatus.

The apparatus consisted of a condenser potential divider, the amplifier and a D'Arsonval galvanometer. The arrangement is essentially that of Figure 1. The potential divider consisted of the coil L , the Weston thermo-galvanometer T, and the condensers C_1, C_2 and C_3. This apparatus has been previously described by Hulburt and Breit.* The potential impressed on the grid of first tube may be found from

$$A = \frac{C_3 \, I}{\omega \, (C_1 C_2 + C_1 C_3 + C_2 C_3)} \qquad (3)$$

in which I is the effective current measured by T.

By coupling L to a suitable electron tube generating set, unmodulated high frequency voltage of a small known amplitude and

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* Phys. Rev. 16, 274, 1920.

frequency was impressed on the grid of the first tube. The high resistance leak r_0 was connected across C_2 to insure a definite value of the grid potential during the experiment. The effect of r_0 upon the impedance of C_2 was negligible because C_2 was large (either .05, .1, or .2 MF) and the frequencies used were of the order of 10^5.

The amplifier was a two-tube one with resistance capacity coupling. The tubes were General Electric Company tubes, Radiatron type UV 201; they were used with the filament current of .94 amperes and had a common plate voltage supply of 52.3 volts. Separate storage cells supplied each filament. The electron emission was found to be sensitive to external temperature changes. It was therefore found necessary to enclose the electron tubes in covered cardboard tubes in order to keep their temperatures constant. The plate battery was shunted by a 1.75 MF condenser C_6. The resistance r_2 was 115×10^3 ohms and r_3 was 360×10^3 ohms. The resistances r_0, r_2 and r_3 were non-inductive being of the type described by Hulburt.* These were found to give satisfactory service. The value of the resistance for high frequency currents was assumed the same as that measured with direct current.

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* Loc. cit.

The change in the value of the rectified high frequency component of the plate current of the second tube of the amplifier, designated by b_0 , was measured by a D'Arsonval galvanometer, G, Figure 1, connected across a resistance r_4 placed in the plate circuit. r_4 was 60,000 ohms. The galvanometer had a resistance of 9.0 ohms and a sensibility of 5.8×10^{-8} amperes per millimeter deflection on a scale 125 cms. distant. P_1 and P_2 Fig. 1 were potential dividers, P_1 serving to keep the plate voltage at the desired value, and P_2 to compensate for the potential drop in the resistance r_4 so that the galvanometer rested approximately at zero. When the grid voltage of the first tube was changed, a deflection of the galvanometer resulted which was proportional to the change in the rectified high frequency component of the output plate current.

It was important that the filament currents remain constant. Any change in these currents resulted in a shift of the operating point of the tubes. The electron tubes were seasoned before every series of readings until a reasonably constant condition of filament current and electron emission was reached. In order to eliminate the error due to the usual slow drift of the galvanometer, the two zero readings were averaged. It was found that the grid leak r_0 gave a constant potential of nearly zero on the grid of the first

tube when its value was 246×10^3 ohms. This value was not critical. For large values of r_0, the value of the grid potential shifted with the necessary variations in the value of C_3. A Kolster decremeter, calibrated by the Bureau of Standards was used to determine the wave-lengths of the high frequency current.

3. Variation of Coupling Capacity.

The reading of the coupling condenser C_4 was varied at each reading, a number of input potentials were impressed on the grid of the first tube and the corresponding galvanometer deflections were noted. From the reading of T, the thermo-galvanometer, and a knowledge of the capacities C_1, C_2 and C_3, the amplitude of the change of the input grid voltage, A was computed, using formula (3). Three sets of readings were taken, at wave-lengths 1016, 3070 and 6235 meters. The resulting curves, with b_0 the ordinates and A^2 the abscissa, are shown in Fig. 2, 3 and 4. It can be seen that for each value of C_4 for all three wave-lengths the $b_0 - A^2$ curves are straight lines. This fact has been established by a large number of similar curves, not shown here. The curves for any one wave-length are plotted from data taken with the potential divider condensers C_2 and C_3 held constant. A change in the value of C_3 caused the curve for any particular value of C_4

to shift and also to change its slope. This is shown in Fig. 3 by the curve marked $C_3 = 211$. This fact can be explained by a shift in the operating point of the first tube because of a shift in the normal value of the grid potential. r_0 had the the value 13×10^5 ohms during these readings. Another point of interest in these curves is that the straight lines do not pass through the origin, although within the limit of experimental error they pass through a common point on the A^2 axis. This seems to indicate a constant error in the determination of A^2 although a check up of the calibrations revealed no differences large enough for compensation. It is also of interest to notice that for each wave-length there is practically the same current range (b_0) but that there is a large range in the value of A^2 ; for 1016 meters, .006 to .016; for 3070 meters, .002 to .005 and for 6235 meters, .005 to .0015 volts.

The main fact, however, remains that the straight lines were obtained, as is predicted by formula (1).

In order to further test formula (1) the slopes of the curves corresponding to each value of C_4 were determined and then plotted against values of C_4 for each of the three wave-lengths as shown in Fig. 5. That is, experimental values of $\frac{b}{A^2}$ are plotted against values of C_4. Then, from formula (1) the theoretical value was computed. Values of the constants not before given, r_1,

the direct current filament to plate resistance of the first tube, was 60 x 10^3 ohms; C_5, the filament-grid capacity of the second tube was 18MMF. This was measured in its socket and included the capacity of its lead wires, which were short, however. As neither n or k were determined experimentally, the computed curve was made to coincide with the experimental curve at C_4 equal to 628MMF. The computed curves are the broken lines. While the agreement between the experimental and computed curve is not exact, it is quite satisfactory, revealing no marked differences in behavior for two of the wave-lengths considered, while for wave-length 3070 m. the agreement is good.

No change in the character of the computed curve was found whether formula (2) or its approximation (1) was used.

4. Variation of Wave-length.

The coupling capacity C_4 was kept at its maximum value of 628 MF, r_2, r_3 and r_4 remained at their former values of 115 x 10^3, 360 x 10^3 and 60 x 10^3 ohms. A series of readings were taken so that the variation of detecting efficiency with wave-length could be determined. The experimental results are given in the full line curve of Fig. 6.

As the curve connecting the square of the input grid potential and the rectified component of output plate current does not pass through the origin, a series of readings was taken at each wave-length, a curve drawn and the slope determined. This slope

is $\frac{b_o}{A^2}$. The experimental curves just mentioned were straight lines within experimental error.

In order to keep the grid potential of the first tube constant for the entire range of wave-lengths used, it was found necessary to fix its value near zero, which was done by making r_0 equal 246×10^3 ohms. This was tested by obtaining the deflection of the galvanometer when the condenser C_2 was short circuited, there being no high frequency current in the input circuit. This test was made when the condensers C_1 and C_3 had values corresponding to the range of wave-lengths used. C_2 was .2MF throughout the run.

The computed curve, shown dotted in Fig. 6, was made to agree with the experimental curve in the neighborhood of 4100 meters. It was computed from formula (2), as the approximate formula (1) differed with it over the range of wave-lengths computed.

The agreement of the two curves is substantial throughout the entire range, and, it is believed, would be even better, if the apparatus had been used with better control over the grid potentials. Thus, the simple theory underlying Hulburt's formula, is in agreement with experiments thus far made.

The curve of detecting efficiency against wave-length

given by Hulburt from 600 to 1600 meters is a straight line. This is in agreement with the curve given in Fig. 6 and also with an unpublished curve carried down to 1100 meters.

It is seen that the detecting efficiency at higher wave-lengths (lower frequencies) becomes independent of the wave-length.

The detecting efficiency was found to be exceedingly sensitive to any changes in the electron tube constants. It would be interesting to determine the detecting efficiency for a positive grid potential on the first tube, where the amplification is a maximum, to see whether the formula held. It would be less difficult, perhaps, to get observations for this condition.

5. Amplification.

It was necessary to test the independence of n with respect to wave-length. By definition

$$n = \frac{b_0}{Eg^2}$$

where b_0 is the rectified component of the output plate current and E_g is the potential variation on the grid of the second tube.

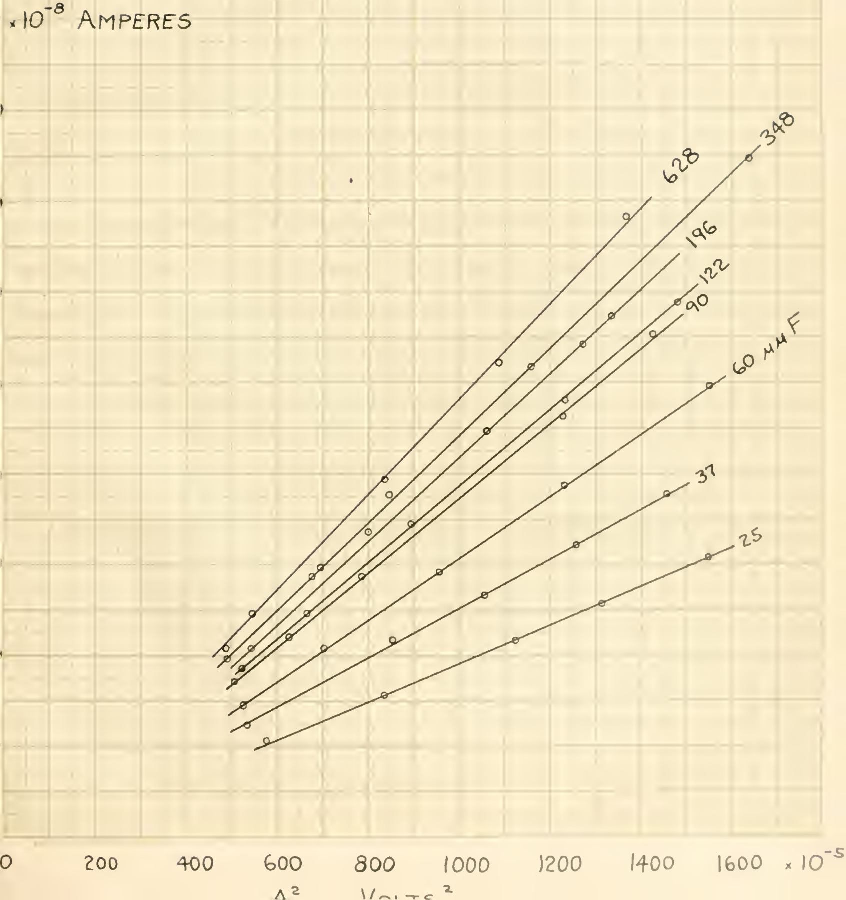
In order to measure n the input voltage was impressed directly on the second tube, the first tube being disconnected, and the output plate current was found for a series of wave-lengths.

As before, sufficient observations were made for each wave-length so that a curve could be drawn and the slope determined. The slope was $\frac{b_0}{E_g^2}$. The curves so determined were straight lines. n was found to be sensibly constant for all wave-lengths as is shown in Curve 3, Fig. 6.

If the ordinate of Curve 1 be divided by the ordinate of Curve 3 at the same wave-length, both of Fig. 6, the quotient is the amplification of the current obtained by the use of the amplifying electron tube. That is, the quotient gives the number of times the rectified component of the plate current, b_0, is increased by the use of two tubes instead of one. The quotients, or current amplifications, are the ordinates on the left margin of Fig. 6. If telephones are used the sound intensity amplification is proportional to the square of these numbers.

This problem was suggested to me by Dr. E. O. Hulburt, now at the State University of Iowa, who derived the formula underlying the investigation.

FIGURE 2
WAVE LENGTH 1016 M.



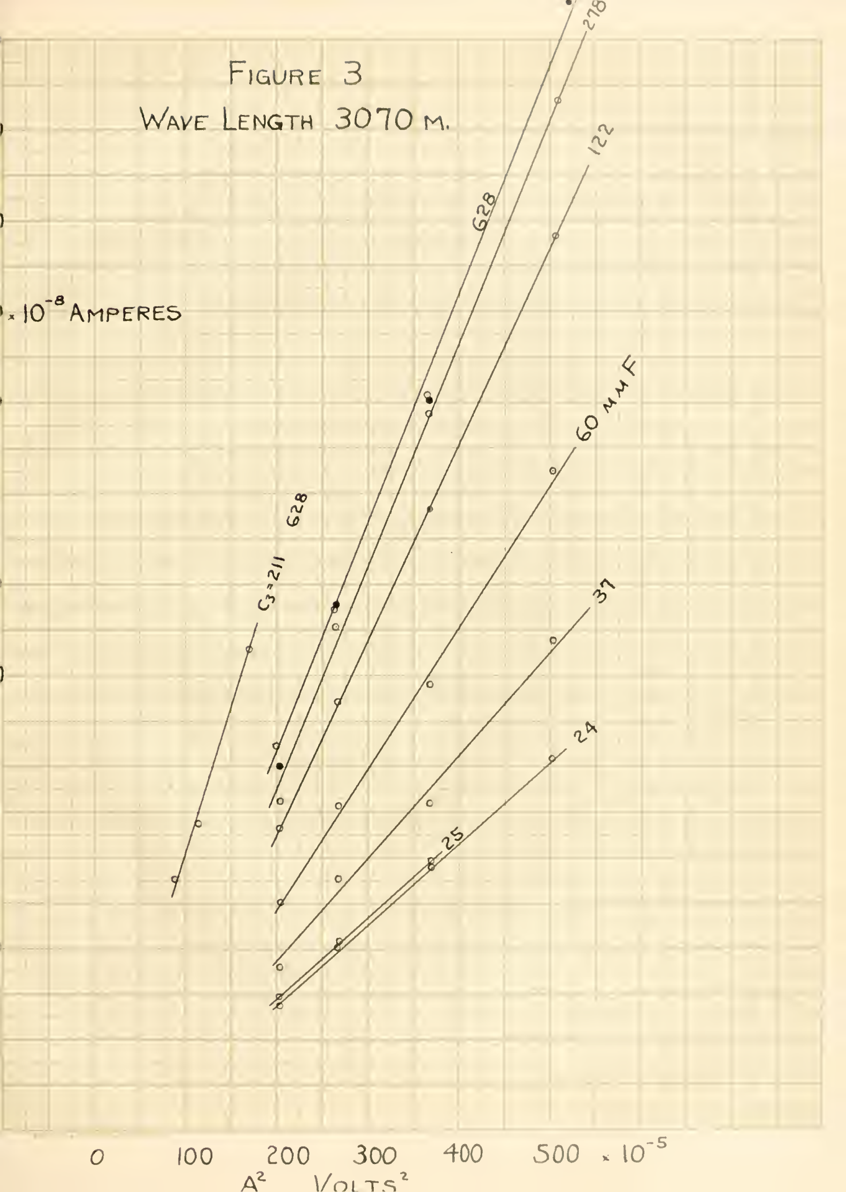


FIGURE 3
WAVE LENGTH 3070 M.
× 10^{-8} AMPERES
278
628
122
60 μμF
628
C_3=211
37
24
25
0
100
200
300
400
500
× 10^{-5}
A^2 VOLTS^2

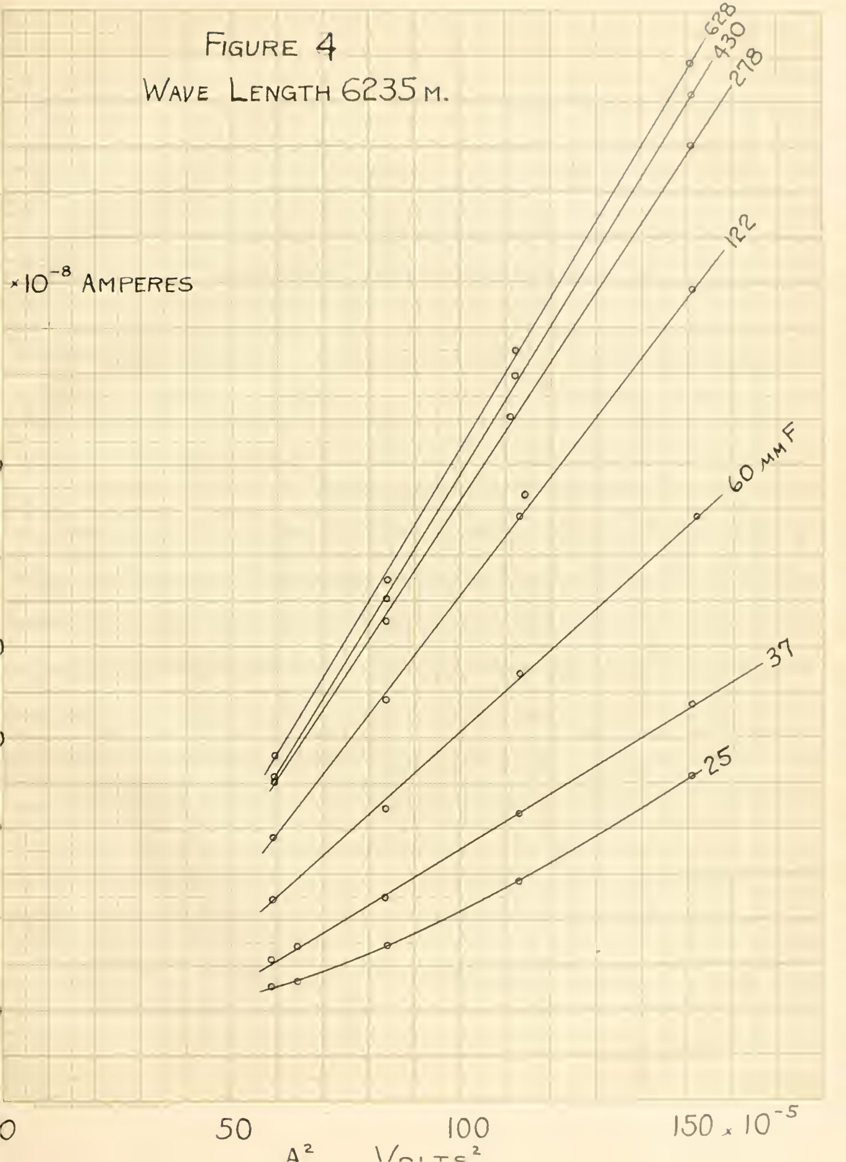


FIGURE 4
WAVE LENGTH 6235 M.
×10⁻⁸ AMPERES
628
430
278
122
60 MMF
37
25
0
50
100
150 × 10⁻⁵
A² VOLTS²

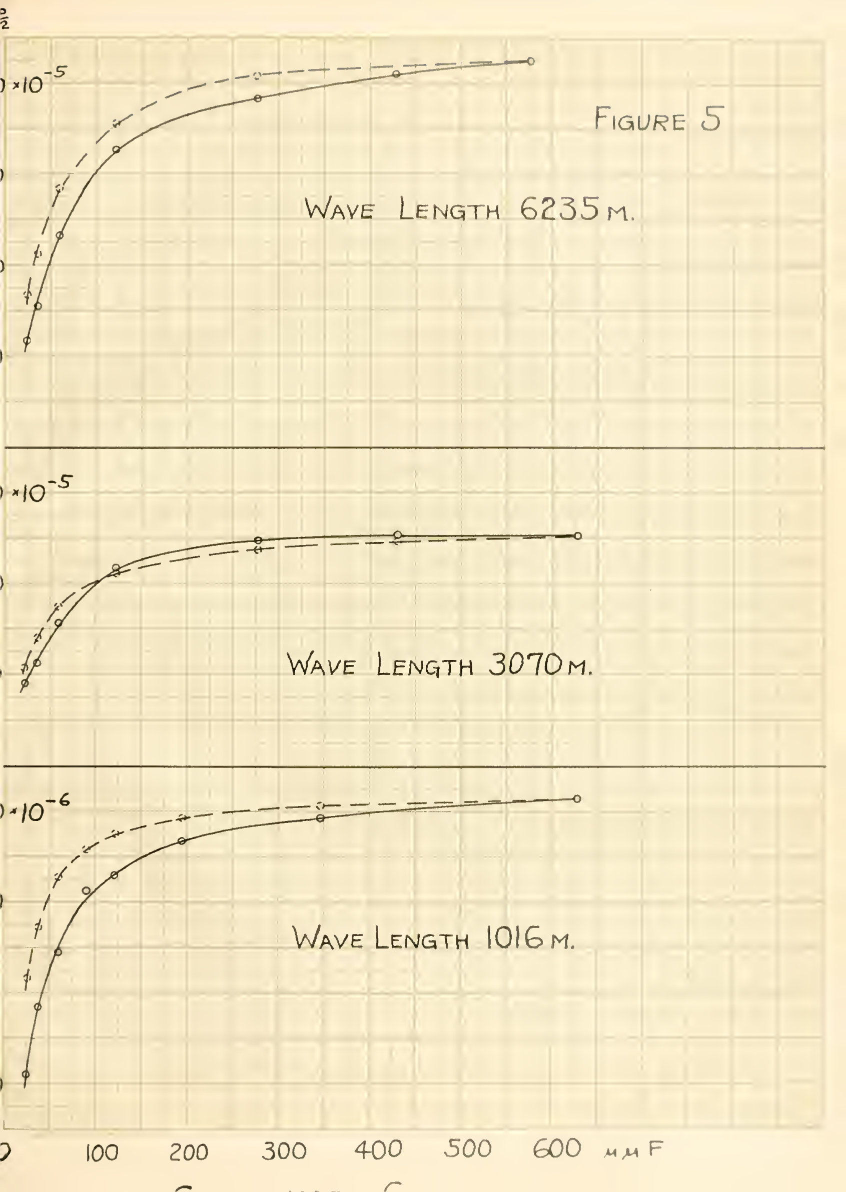
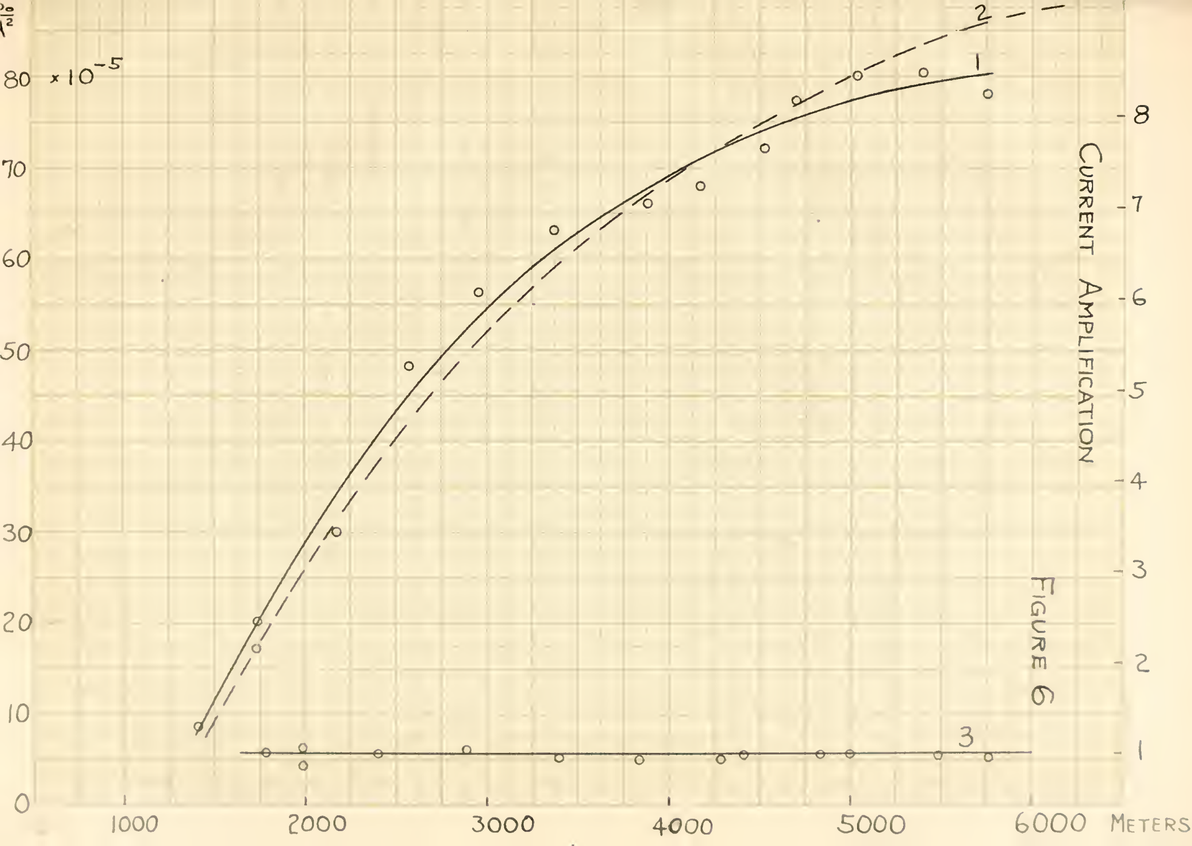


FIGURE 5
×10^-5
WAVE LENGTH 6235 M.
×10^-5
WAVE LENGTH 3070 M.
×10^-6
WAVE LENGTH 1016 M.
100
200
300
400
500
600
μμF



CURRENT AMPLIFICATION
× 10⁻⁵
METERS
0
10
20
30
40
50
60
70
80
1000
2000
3000
4000
5000
6000
1
2
3
4
5
6
7
8

FIGURE 6

Biographical Note.

William George Brombacher, son of Henry and Elizabeth (Case) Brombacher was born in Cleveland, Ohio February 23, 1891. He received his early education in the Chicago High Schools. In 1915 he received the degree of Bachelor of Arts from Lake Forest College with Shield Honors, and in 1917 the degree of Master of Arts from the same college. During the year 1918 he was in the United States Army, stationed at the Bureau of Standards, afterwards filling the position of Assistant Physicist at the Bureau.

In 1919 he entered the Johns Ho pkins University as a graduate student and as an Instructor in Physics. He followed the courses of Professors Ames, Wood and Associate Professor Pfund in Physics, Associate Professor Murnaghan in Mathematics and Professor Reid in Geophysics.